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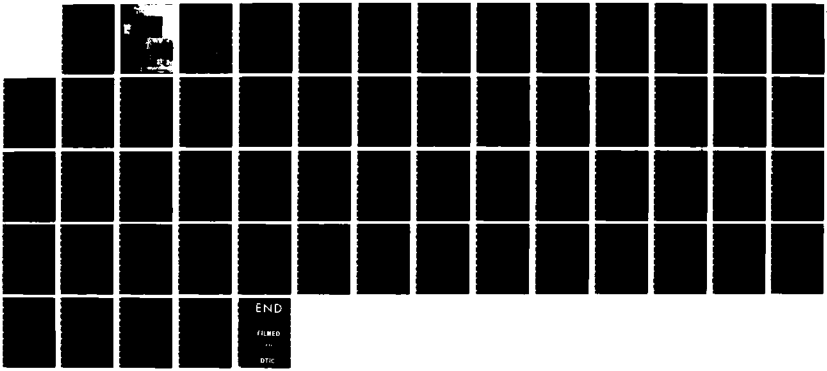
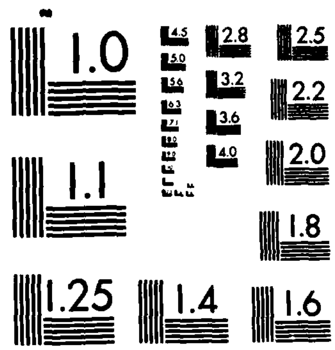
UNCLASSIFIED CSSA-ASTRO-85-26-REV N00014-85-K-0111 F/G 3/2 NL





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TWO CLASSES OF GAMMA-RAY/PROTON FLARES: IMPULSIVE AND GRADUAL

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Center for Space Science and Astrophysics
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(Revised in November 1985)

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Grant NGL 05-020-272
Grant NAGW-92

OFFICE OF NAVAL RESEARCH
Contract N00014-85-K-0111

ABSTRACT

We have studied various properties of ~~γ-ray/proton~~ gamma ray/proton flares, which produce nuclear ~~γ-rays~~ gamma rays and/or interplanetary energetic protons. We have found that there exist two classes of ~~γ-ray/proton~~ (GR/P) flares, with each class having many distinct characteristics in common. Gradual GR/P flares (so named because of gradual variations of hard X-ray fluxes with duration of spike bursts longer than 90 s) have the following characteristics: long duration (> 10 min) hard X-ray and microwave emission, gradual variation of microwave flux, relatively large ratios of microwave to hard X-ray fluxes, large H-α (alpha) areas, long-duration soft X-ray emission (> 1 hr), hard X-ray emission from extended coronal loops, interplanetary type II emission, coronal mass ejections, and production of large numbers of interplanetary energetic protons. Impulsive GR/P flares display directly opposing behavior in the above respects. However, the two classes of GR/P flares have a few characteristics common to both of them. We have reached the following conclusions: (1) In both classes of GR/P flares protons are accelerated in closed magnetic loops during the first phase by the second-step mechanism, and these protons have a low escape probability and produce γ-rays interacting with the solar atmosphere. (2) In gradual GR/P flares additional protons are accelerated in the high corona by shock waves, and these protons easily escape into interplanetary space. This is the main reason the correlation is poor between γ-ray fluence and interplanetary proton flux.

I. INTRODUCTION

The first three well-observed γ-ray line (GRL) flares (1972 August 4 and 7; 1978 July 11) were two-ribbon flares, and the duration of their hard X-ray emission was quite extended (cf. Chupp _et al_. 1973; Hoyng _et al_. 1976; Hudson _et al_. 1980). These characteristics are often observed in flares producing interplanetary (IP) protons (e.g., Svestka 1976). Therefore, it was somewhat surprising when the first GRL flares (1980 June 7 and 21, 1980 July 1) observed with the _Gamma Ray Spectrometer_ (GRS) aboard _SMM_ were found to be small in H-α importance and impulsive in hard X-ray emission (Forrest _et al_. 1981; Chupp 1982; Chupp 1983; Forrest and Chupp 1983). Since then, GRS has also detected γ-ray lines from many gradual flares (Chupp 1982, 1983). The morphology of hard X-ray time profiles of the _SMM_ γ-ray line flares (those with observable nuclear γ-rays) has been studied by Bai and Dennis (1985). Physics of γ-ray emission during solar flares has been studied by Ramaty, Kozlovsky, and Lingenfelter (1975) and Ramaty _et al_. (1983).

In view of the foregoing, one may wonder whether there are two classes of γ-ray line flares. Ohki _et al_. (1983) attempted to classify flares into impulsive and gradual on the basis of the characteristic time scales of hard X-ray flux variations. Along the same lines, Yoshimori _et al_. (1983) pointed to the 1981 April 4 flare as an example of an impulsive GRL flare and the 1981 April 27 flare as an example of a gradual GRL flare. But such a classification is not very meaningful unless it is shown that flares of different classes have many distinct characteristics signifying differences in underlying physical processes. Studying the various properties of GRL flares, Bai and Dennis (1985; Paper I) found that GRL flares as a group possess a set of distinct characteristics. Although in Paper I we grouped

GRL flares into impulsive, intermediate, and gradual flares for the convenience of discussion, we did not attempt to determine whether or not more than one class of GRL flares exists.

The direct evidence that protons and heavy ions are accelerated to energies above several MeV/nucleon during a solar flare comes either from observation of nuclear γ rays or observation of interplanetary energetic particles. Depending on the kinds of observation, we call flares that accelerate protons and ions GRL flares or proton flares. Chupp (1982) labeled them Class I and Class II proton flares, respectively. For some flares we observe both manifestations, and for others we observe just one. Therefore, it seems convenient to devise a name to refer to all of them. Hereafter, we use the term "γ-ray/proton (GR/P)" flares to refer to flares for which we have direct observation of nuclear γ rays and/or interplanetary protons or indirect but convincing evidence of proton acceleration. However, we will still use the term "GRL flares" to refer specifically to flares from which 4-8 MeV excess photons have been observed.

In this paper we investigate various observational properties of GR/P flares to see whether it is appropriate to classify them into impulsive and gradual flares. Of the 19 GRL flares studied in Paper I, six were considered gradual flares. It would not be very convincing to claim from the study of such a small number of flares that they constitute a class of their own, even though they have common characteristics. Therefore, we first find more flares similar to gradual GRL flares; and then by studying various properties of these flares, we conclude that they constitute a separate class. In Section II we reevaluate whether GRL flares are different from other flares. In Section III we search for flares with gradual hard X-ray time profiles and then show that they share many common

characteristics. Among the gradual flares, the only difference between those with observable nuclear γ rays and those without is that HXRBS peak rates are greater than 4500 counts/s for the former, while they are less for the latter. Because the gradual flares share additional common characteristics not shared by impulsive GRL flares, we propose to classify GR/P flares into two classes. In Section IV we examine differences between the two classes of GR/P flares in phenomena occurring in the high corona and interplanetary medium. By examining the ratio of the number of interplanetary protons to the number of γ-ray-producing protons, we find that it is small ($\lesssim 10^{-2}$) for impulsive GR/P flares, but it is relatively large ($\gtrsim 1$) for gradual GR/P flares. We also find that gradual GR/P flares are associated with many phenomena occurring in the high corona and interplanetary medium. Our summary and conclusions are presented in Section V.

II. ARE GRL FLARES DIFFERENT FROM OTHER FLARES?

The answer to this question is important. If during all flares substantial numbers of protons and heavy ions are accelerated to γ-ray-producing energies, the GRL flares, which were selected by the GRS threshold, are not likely to be very much different from other flares. On the other hand, if only a small fraction of flares produce nuclear γ rays, GRL flares are likely to exhibit some properties not shared by most flares in general. One problem arising when we compare GRL flares with non-GRL flares is that GRL flares constitute a pure sample while the rest of flares are a mixed sample. Among "non-GRL flares" with peak HXRBS rates > 10000 (or 5000) counts/s, which were comparison groups in Paper I, there are genuine non-GRL flares and flares with nuclear γ ray fluxes just somewhat below the GRS threshold. However, as long as genuine non-GRL flares constitute the absolute majority of the comparison group, one can expect to see the differences.

Addressing this question in Paper I, we studied the characteristics of GRL flares. Table 1 shows various properties of GRL flares. Although this table is basically the same as Table 1 of Paper I, we have reformatted it with some additional information. The two flares on 1980 November 12 and December 18, which were included in Table 1 of Paper I, are omitted here, because the most recent analysis gives only upper limits to their 4-8 MeV excesses (Forrest 1985). Also, note that the definition of the total duration of hard X-ray emission is somewhat different from that used in Paper I. From this table, we see that GRL flares as a group possess the following common characteristics (cf. Paper I):

1. Delay of high-energy X-rays with respect to low-energy (50 keV) X-rays (or, equivalently, spectral hardening of hard X-ray emission through the peak and on the decay);

2. Flat spectra of hard X-ray emission (the average power-law spectral index measured at the time of hard X-ray peaks is 3.5);

3. Association with type II and type IV radio bursts;

4. HXRBS peak count rates > 5000 counts/s; and

5. Intense microwave emission with peak flux densities $\sim >$ 500 sfu at $\sim$ 9 GHz.

The last two characteristics may be attributed to the GRS sensitivity threshold. That is, all the GRL flares in Table 1 were selected because they produced γ rays above the GRS threshold. Let us reevaluate the first three characteristics of GRL flares. (1) Association with type II and type IV radio bursts. In Appendix 1 of Paper I, we discussed how to evaluate the significance of association with type II or type IV radio bursts. Of the 11 impulsive GRL flares in Table 1, eight produced type II radio bursts. On the other hand, of the 47 non-GRL flares observed during 1980 and 1981 to have HXRBS peak rates > 5000 cts/s, only 12 produced type II bursts (cf. Paper I). Using Eq. A1 of Paper I, we find that the probability of this being due to chance is only 0.47 percent. (2) Spectral index difference. In evaluating the significance of the difference between measured quantities of a certain trait of two samples, one can apply Student's difference test (e.g., Brandt 1970). Applying this test to the spectral index difference between the 11 impulsive GRL flares in Table 1 of the present paper and the 11 non-GRL flares in Table 2 of Paper I, we find

that the difference is significant at a 99.5 percent confidence level. If we compare all the 17 GRL flares in Table 1 with the 11 non-GRL flares, we find that the spectral index difference is significant at 99.9 percent confidence level. If we choose other comparison groups such as all the flares with HXRBS peak rates > 10000 counts/s (or 5000 counts/s) observed during the first year of SMM operation, the confidence level increases. (3) Soft-hard-harder behavior of hard X-ray spectra. We have discussed this in detail in Paper I. By showing that this spectral behavior is observed from almost all the gradual GR/P flares, we shall establish an extremely close link between nuclear γ-ray emission and soft-hard-soft behavior of hard X-ray emission.

Forrest (1983) recently showed that there is a good correlation between the fluence of hard X-rays > 270 keV and the fluence of excess 4-7 MeV γ rays, and that the GRS events with detectable > 270 keV hard X-rays but without detectable 4-7 MeV γ rays have rather low fluences of hard X-rays (cf. review by Chupp 1984). From these results, they concluded that nuclear γ rays must have been emitted by all the GRS flares (flares with > 270 keV hard X-rays detected by GRS) and only the threshold effect prevented them from detecting nuclear γ rays during weak GRS flares. If we extrapolate substantially, we may speculate that possibly all flares emit nuclear γ rays. In light of the findings of Forrest _et al_. and the importance of the question, in the following we shall study the properties of GRS flares.

Let us first examine hard X-ray spectra. In Figure 1 distributions of hard X-ray spectral indices measured at hard X-ray peaks are shown for three groups of flares observed during the first year of SMM operation (1980.2.19-1981.2.19): all non-GRL flares with peak rates > 1000 counts/s; GRS flares with HXRBS peak rates > 1000 counts/s; and GRL flares. In

plotting this figure, we have not included the flares whose actual hard X-ray peaks were not observed by the HXRBS for one reason or another. For the GRS flares we used the list in Rieger (1982). From Figure 1 we see that GRS events have much flatter hard X-ray spectra than flares in general. (Because all but two GRS events have HXRBS peak rates > 1000 counts/s, non-GRS flares with HXRBS peak rates > 1000 counts/s constitute a reasonable comparison group.) The hard X-ray spectra of the GRS flares are flat in a manner similar to those of the GRL flares. Because the GRS threshold energy is rather high (~ 270 keV), GRS is expected to select out flares with flat hard X-ray spectra. Therefore, if we accept the finding of Paper I that flares producing nuclear γ rays have different characteristics, with one of them being flat hard X-ray spectra, then we expect that a large fraction of GRS flares must have produced nuclear γ rays.

One may argue that GRL flares have flat hard X-ray spectra because the search for GRL flares was made within the GRS flares. However, because the correlation between the fluences of > 270 keV hard X-rays and 4-7 MeV excess γ rays is quite good (Forrest 1983; Chupp 1984), it is quite unlikely that nuclear γ rays can be detected from a substantial number of non-GRS flares without detectable > 270 keV hard X-rays.

Now, let us investigate the association with type II and type IV radio bursts for flares with HXRBS peak rates > 1000 counts/s. The results are shown in Table 2 for gradual flares, GRS flares, and non-GRS flares observed during the first year of SMM operation. Here we separate gradual flares, because they are different from the rest as will be shown in the following sections. We find that a much larger proportion of GRS events than non-GRS flares is associated with type II or type IV bursts. According to Equation A1 of Appendix A of Paper I, the probability that

this is due to chance is 2.0 percent for type II bursts and 0.08 percent for type IV bursts.

From the above comparisons, we find that GRS flares are sufficiently different from other flares. Therefore, it may be justifiable to claim that a large fraction of GRS flares may have produced nuclear γ rays, but it is not justifiable to extrapolate the claim to all the flares.

One can propose the following hypothesis: (1) During all flares both electrons and protons (and heavy ions) are accelerated by a single mechanism. (2) There is a good coupling between the electron energy spectrum and proton energy spectrum. (3) Therefore, flares with flat hard X-ray spectra have flat energy spectra of protons and heavy ions; and consequently they are likely to produce observable nuclear γ rays. However, this hypothesis does not provide a ready explanation of why GRL flares are different from other flares regarding association with type II and type IV radio bursts and soft-hard-harder behavior of hard X-ray spectra. Furthermore, the following facts cast serious doubts on the possibility of close coupling between the proton energy spectrum above 1 MeV and the electron spectrum below 500 keV. Compared at the same energies above 1 MeV, the number of protons deduced from γ-ray observation is two or three orders of magnitude larger than the number of bremsstrahlung emitting electrons. Although we do not have a direct measure of proton numbers at low energies, from an energetics standpoint we can rule out the possibility that protons are far more numerous than electrons in the 20 - 500 keV range (see, for example, Ramaty et al. 1980). It is quite difficult to envision that a single mechanism can somehow introduce different spectral relations between protons and electrons at different energy regimes while the electron spectrum in the low-energy regime is closely correlated with the proton spectrum in the high-energy

regime.

The flare-size distribution histograms shown are for HXRBS total counts, > 270 keV fluences, and 4-7 MeV excess γ-ray fluences in Figure 2 (a, b, and c, respectively). HXRBS total counts were taken from Dennis et al. (1983), and > 270 keV fluences and 4-7 MeV excess γ-ray fluences were taken from Figure 3 of Chupp (1984). The slopes of the size distribution histograms for > 270 keV hard X-rays and 4-7 MeV excess γ rays are quite similar, as expected from the proportional correlation between the two quantities. However, the slope of Figure 2a is significantly steeper than those of Figures 2b or 2c. The number of flares increases much more rapidly with decreasing total HXRBS counts than with decreasing nuclear γ-ray fluences. If we extrapolate the straight lines indicating power-law size distribution, ~ 2500 flares are in the top four decades of the dynamic range of HXRBS total counts (10^4 - 10^8), whereas only ~ 300 flares are in the top four decades of the dynamic range of 4-8 MeV fluences (10^{-2} - 10^2 photons/cm^2). Even if the power-law size distribution extends two decades more without leveling off, a γ-ray detector 100 times more powerful than the GRS would have detected nuclear γ rays from only about 300 flares during the same time period. This clearly indicates not all flares emit nuclear γ rays.

Historically, while many researchers studied the characteristics of proton flares, McCracken and Rao (1970) claimed that essentially all flares accelerate energetic IP particles and that it is only a matter of sensitivity of our detectors whether we detect them or not. History proved McCracken and Rao's claim to be wrong. Satellite-borne proton detectors have been improved in sensitivity by large factors, but we still detect energetic IP particles only after a small fraction of flares. One can see a parallel between McCracken and Rao's position and the view that all

flares emit nuclear γ rays.

A simple explanation for the characteristics of GRL flares is as follows: For all flares the bulk of energy in accelerated particles resides in low-energy ($\sim$ 30 keV) electrons. According to the concept of second-step acceleration (Bai and Ramaty 1979; Bai 1982; Bai et al. 1983b), during a special class of flare, an additional mechanism further accelerates a fraction of high-energy electrons initially accelerated by the primary (or first-step) mechanism and accelerates protons and heavy ions to γ-ray-producing energies. According to this concept, > 270 keV fluences and nuclear γ-ray fluences are well correlated because relativistic electrons and energetic ions are due to the same mechanism. Along the same line, for these flares hard X-ray spectra are flat because the second-step mechanism accelerates high-energy electrons.

III. CHARACTERISTICS OF GRADUAL GR/P FLARES

a) Microwave-Richness Index

Figure 3 is a correlation diagram between the HXRBS peak count rate and the peak flux of ~ 9 GHz microwaves for flares observed during 1980-1981. Each dot represents a single flare. The HXRBS peak count rates are from the HXRBS Event Listing (Dennis *et al*. 1983), and the peak fluxes of ~ 9 GHz microwaves are from the *Solar Geophysical Data*. Among the flares that have been only partially observed by HXRBS because of the satellite's eclipses, passage through the South Atlantic Anomaly, or data gaps, the ones without hard X-ray data covering the microwave peak times are not included in this figure. Although we see a lot of scatter in Figure 3, we can see a positive correlation between the two quantities (cf. Kane 1973).

We define the microwave-richness index (MRI) as follows:

$$\mathrm{MRI} = \frac{\text{peak flux density of 9 GHz microwaves (sfu)}}{\text{HXRBS peak count rate (counts/s)}} \times 10 \quad .$$

When defined as such, the median value of MRIs is 0.85. In plotting the points in Figure 3 and in defining MRI, we took the peak flux density of ~ 9 GHz microwaves of a given flare and the HXRBS peak rate of the same flare, even when the microwave peak flux and HXRBS peak flux are observed at different bursts of the same flare. This procedure was used for the sake of convenience, but we suggest the following justification. Suppose that a flare is composed of two bursts. Let us denote the maximum microwave flux densities of the first and second bursts as M_1 and M_2, and the maximum HXRBS count rates of the first and second bursts as X_1 and X_2. Suppose that $M_1 > M_2$ but $X_2 > X_1$. We find that $M_1/X_1 > M_1/X_2 > M_2/X_2$. Therefore, when we define the MRI of this flare as $(M_1/X_2) \times 10$, it is

smaller than the MRI of the first burst $(M_1/X_1) \times 10$ but larger than the MRI of the second burst $(M_2/X_2) \times 10$. Hence, the MRI of the flare we adopt in this paper is somewhat of an average of the MRIs of the two bursts of this flare.

b) Search for Gradual GRL Flares

The GRL flares in Table 1 are grouped into impulsive and gradual flares. Although the six gradual flares are different from the impulsive flares in some respects, we need a large number of gradual flares in order to study additional properties and to claim convincingly that gradual flares constitute a separate class. Therefore, we decided to search for a large number of gradual flares having similar properties. If the fact that all the GRL flares have HXRBS peak rates > 5000 counts/s is due to the threshold effect of the GRS, there may be many gradual flares producing nuclear γ-rays below the GRS threshold among the flares with HXRBS peak rates < 5000 counts/s.

Because the hard X-ray time profiles of the gradaul GRL flares in Table 1 are characterized by their gradualness (with spike duration > 90 s) and long total duration (> 10 min), we searched for flares with such hard X-ray characteristics by visually inspecting hard X-ray time profiles compiled by the HXRBS group. Some flares show impulsive time profiles in the beginning and gradual time profiles later. Among those flares, we selected only those showing gradual behavior at the largest hard X-ray spike bursts. We also excluded from our study the flares whose hard X-ray peaks were not observed by HXRBS. We limited our search to moderate and intense flares that fall above the cutoff line in Figure 3 for 1980 and 1981. Gradual flares found in this way are indicated w'th "x" designations in this figure. We find that gradual flares are "microwave-rich"; their

MRIs are all > 1, and their median MRI is ~ 5. By comparing 17 GHz peak fluxes with 67-152 keV hard X-ray fluxes (measured with Hinotori), Kai, Kosugi, and Nitta (1984) also noticed that for gradual flares the microwave-to-hard-X-ray-flux ratios are higher than average. Notice here that all but two of the microwave-rich flares (with MRI > 4) of 1980 and 1981 are gradual flares. Initially, microwave-richness was used as a convenient and efficient means of selecting gradual flares (Bai, Kiplinger, and Dennis 1984). In the present study also we have investigated only flares with MRI > 3.5 in our search for gradual flares in 1982. The various properties of gradual flares found in this way are shown in Table 3.

c) Hard X-Ray Characteristics of Gradual Flares

Gradual flares are found to have the following common characteristics in their hard X-ray signatures:

1. The hard X-ray time profiles show gradual behavior (cf. Figs. 4-7). This is one of the selection criteria. To quantify this gradual behavior, we selected the strongest hard X-ray burst of each flare and measured its duration (full width at 10 percent of the maximum) using the time profiles of total count rates of HXRBS channels 5-7. The durations determined in this way are listed in Table 2. They range from 1.5 to 13 min, considerably longer than the durations of impulsive flares, which are of the order 0.2 min. Here 1.5 min is the lower limit we adopted.

2. The total hard X-ray duration of the whole flare measured at the 10 percent level is also very long, 12 to 45 min, compared with ~ 2 min for impulsive flares. The gradual flares selected here are similar to extended-burst flares of Hoyng et al. (1976).

3. For all the gradual flares the X-ray spectrum gets harder with time

through the peak and on the decay (see Figs. 4-7). Such spectral behavior was described as a soft-hard-harder trend in Paper I, which contrasts with the soft-hard-soft trend exhibited in ordinary flares (Kane and Anderson 1970). Such spectral hardening is equivalent to progressive delay of high-energy X-rays (Paper I). Delays in Table 3 were calculated by comparing hard X-ray time profiles for the energy band ~ 307-516 keV (channel 10-15) with those of the energy band ~ 58-137 keV (channel 3-5). All the flares in Table 3 show hard X-ray delays and spectral hardening, with the possible exception of the 1981 June 22 flare. The hard X-ray time profile of this flare shows that around the hard X-ray maximum three hard X-ray bursts are superposed upon one another making it difficult to discern any spectral hardening. The 1980 November 14 flare (No. 21 in Table 3) exhibits spectral hardening, but it is difficult to estimate the high energy delay because this flare shows significant counts for the first 5 channels.

4. Gradual flares have flat hard X-ray spectra. As seen in Figures 4-7, the spectral index of a given flare changes with time, but we adopt the spectral index measured at the hard X-ray peak as the representative spectral index. The spectral indices shown in Table 2 range from 2.8 to 4.5, with the average being 3.5. The median value of the spectral indices determined in the same manner for flares with HXRBS peak rates > 1000 counts/s is 4.6 (Figs. 1 and 8). The probability that the spectral indices of all the 23 gradual flares would be less than this median by random chance is $(0.5)^{23} = 1.2 \times 10^{-7}$.

5. The HXRBS peak count rates of gradual flares span two orders of magnitude, and the lowest HXRBS peak rates found for the gradual flares are an order of magnitude lower than the counterparts of the GRL flares studied in Paper I (also see Table 1).

Here discussions on hard X-ray time profiles of gradual flares are needed for clarification. Even in impulsive flares, during the decay phase X-ray time profiles dominated by thermal radiations at low energies (< 20 keV) become gradual. The gradual flares described in this paper, however, show gradual behavior in hard X-ray time profiles. Some flares show impulsive behavior at the begining (cf. Figs. 4 and 7), but some flares show no impulsive behavior whatsoever (cf. Fig. 5 for the 1981 May 8 flare; Tsuneta et al. 1984 for the 1981 May 13 flare). Therefore, it should not be interpreted that the gradual behavior of hard X-ray emission is a phenomenon occurring only in the late phase of a flare. In our selection of gradual flares, we excluded flares that show impulsive behavior during the most intense spike burst and gradual behavior during later spike bursts with less intense hard X-ray emission, such as the flares of 1980 May 21 2056 UT and 1981 July 19 0534 UT. Flares with gradual behavior in the so-called secondary peak (Cliver 1983) are, therefore, not included. As far as hard X-ray emission is concerned, the only distinction between gradual flares and impulsive GRL flares is that the time scale of gradual flares is larger. If we reduced the time scales of gradual flares by a factor of five or ten, we would not be able to distinguish them from impulsive GRL flares judging from hard X-ray characteristics only. In summary, gradual hard X-ray emission of the gradual flares is a phenomenon of the main phase (or first phase). (de Jager (1985) calls this phase the impulsive phase even though in some flares a gradual behavior is apparent.)

A few points regarding hard X-ray spectra and hard X-ray directivity are worth discussing here. First, among both GRL flares in Table 1 and gradual flares in Table 3 the spectrum does not vary significantly with the HXRBS peak count rate. Second, we do not find any significant spectral

variation with solar longitude although we notice that the two impulsive GRL flares with the flattest spectra occurred near the limb. Third, if we count the number of flares according to their solar longitudes in 30^{o} bins from the central meridian, for the impulsive GR/P flares we find two flares in the 0^{o}-30^{o} bin, three in the 30^{o}-60^{o} bin, and six in the 60^{o}-90^{o} bin; and for the gradual flares in Table 3 we find four flares in the 0^{o}-30^{o} bin, eight in the 30^{o}-60^{o} bin, and eleven in the 60^{o}-90^{o} bin. Although this shows that more GR/P flares occur near the solar limb, we do not have enough statistics to draw any firm conclusion about the directivity of hard X-ray emission from GR/P flares. According to Vestrand et al. (1984), a larger number of GRS flares have been observed near the limb than in a case of a uniform distribution along the solar longitude.

d) Other Characteristics of Gradual Flares

Peak flux densities of ~ 9 GHz gradual are given in Table 3. We have chosen 9 GHz because it is in the frequency region well covered worldwide, and in most flares it is near the turnover frequency. Delay times of microwaves were determined visually from superposed microwave and hard X-ray (60-135 keV) time profiles. For the flares for which we have not collected microwave time profiles, the microwave delay column is left blank. The microwave time profiles at different frequencies have sometimes different delays. However, above 9 GHz microwave delays are almost independent of frequency, and in most cases they are slightly longer than the delays of higher energy X-rays. This can be explained if microwaves are mainly produced by electrons with energy > 500 keV. In three cases (events 7, 8, and 19 of Table 3), microwave delay times are unusually large. In these flares some high-energy electrons may be trapped in low-density loops, where they emit microwaves. Those electrons have long

lifetimes against Coulomb energy loss and do not emit appreciable amounts of X-rays. A quantitative analysis of this scenario is necessary, which is beyond the scope of the present paper.

Soft X-ray classes and durations are given in Table 3. We can see that the peak soft X-ray fluxes are positively correlated with the HXRBS peak count rates. The duration of soft X-ray emission shown in Table 3 is the interval between times when the soft X-ray flux of the 1-8 Å band is 10 percent of the maximum flux. For gradual flares with intense soft X-ray emission, the duration as determined above is much shorter than the duration during which the soft X-ray emission is above the background. We adopt the full width at 10 percent of the maximum as the duration so as not to be prejudiced against gradual flares with less intense soft X-ray emission. The gradual flares, having soft X-ray durations ranging from 0.8 to 6.0 hours, are soft X-ray long-decay events (LDEs), as characterized by Kahler (1977).

e) Summary of Characteristics of Gradual Flares

We summarize the characteristics of gradual flares shown in Table 3:

1. Progressive delay of higher energy X-rays (or, equivalently, hardening of the X-ray spectrum; cf. Figs. 4-7).

2. Flat hard X-ray spectrum. The average spectral index is 3.5. This is about the same as that of GRL flares (3.4; Paper I), but much smaller than the median value for all the flares with HXRBS peak count rates > 1000 counts/s (Fig. 1).

3. Association with type II and type IV radio bursts. Fifteen of the 23 gradual flares produced type II bursts, and 17 of them produced type IV bursts. All but three of the gradual flares produced either type II or type IV bursts.

4. Gradual behavior of the hard X-ray time profiles (see Figs. 4-7). As one of the two selection criteria, we required the duration of the strongest hard X-ray bursts be longer than 1.5 minutes. Note here that the typical duration of spike bursts of ordinary flares is of order 10 seconds, and in extreme cases the spike burst duration is as small as 0.05 s (Kiplinger et al. 1983).

5. Long duration of hard X-ray emission (> 10 min). This was the other selection criterion.

6. Long decay times of soft X-ray emission. All the flares in Table 3 are LDEs (long decay events), in accordance with the definition of Kahler (1977).

7. Large H-α areas. The flare number distribution in H-α importance is as follows: two flares with importance S, nine with importance 1, nine with importance 2, and two with importance 3. Of the two sub-flares, one was located at the limb, and the other produced the lowest hard X-ray flux among the gradual flares.

8. Long delay of microwave time profiles with respect to low-energy (~ 50 keV) hard X-rays. In general, the delay times of microwave time profiles are slightly longer than those of high-energy hard X-ray time profiles, but in three cases the microwave delay times are unusually long (~ 300 s).

9. Emission of nuclear γ rays. Gradual flares are arranged in Table 3 in order of HXRBS peak rate. When ordered in this manner, the top nine gradual flares are found to have produced observable nuclear γ rays (cf. Rieger 1982; Share et al. 1983).

10. Large MRIs. The median MRI of gradual flares is 5, compared with 0.85 for all the flares in Figure 3.

It is remarkable that the flares in Table 3, which were chosen by two

criteria (gradual and long-duration hard X-ray time profile), share so many common characteristics. The first three characteristics are exactly those of the GRL flares found in Paper I. Considering the foregoing and the fact that the gradual flares with HXRBS peak rates > 5000 counts/s have all emitted observable amounts of nuclear γ rays, we conclude that even the gradual flares with HXRBS peak rates < 5000 counts/s must have emitted nuclear γ rays, albeit below the GRS threshold.

Comparing the gradual flares in Table 3 with the GRL flares in Table 1, we find that gradual flares are different from impulsive GRL flares in many respects. Of the five gradual flares observed with Hinotori, Ohki et al. (1983) noticed that during those flares hard X-rays were mainly emitted from large flare loops and that high-energy X-rays were delayed with respect to low-energy (~ 50 keV) hard X-rays. Pointing out these three common characteristics, Tanaka (1983) classified them as C-type flares. All five gradual flares reported by Ohki et al. were also observed with SMM and are included in the present study as gradual GR/P flares. Because hard X-ray emission from the extended loops is found only for C-type flares, and all of them share the other characteristics of gradual flares, we infer that hard X-ray emission from extended loops is one of the characteristics of gradual flares. Studies by Hudson (1978), Hudson, Lin, and Stewart (1982), and Frost and Dennis (1971) are consistent with this conclusion.

IV. PHENOMENA OCCURRING IN THE HIGH CORONA AND INTERPLANETARY MEDIUM

a) Ratio between the Number of Interplanetary Protons and the Number of Gamma-Ray-Producing Protons

One of the puzzles emerging from observations with SMM and other spacecraft is that the correlation is very poor between the number of protons as deduced from γ-ray observations and the number of interplanetary protons as deduced from in situ measurements (von Rosenvinge et al. 1981; Pesses et al. 1981; Cliver et al. 1983). Because impulsive and gradual GR/P flares are different in many respects, we decided to see whether the ratio of the two proton populations is different for these two classes of GR/P flares. We found that there are indeed significant differencs, as shown below.

For impulsive GRL flares, γ-ray-producing protons outnumber interplanetary energetic protons by orders of magnitude. Among the impulsive GRL flares observed from 1980 through 1981, only those observed on 1980 June 7, June 21, and November 6 are known to have produced detectable interplanetary protons. And even for those flares the interplanetary proton numbers are smaller by orders of magnitude than the numbers of protons interacting to produce γ rays. Many impulsive GRL flares that occurred in regions magnetically well connected to the spacecraft with proton detectors did not register noticeable interplanetary protons (e.g., the 1980 July 1 flare; von Rosenvinge et al. 1981).

On the other hand, for gradual flares, the opposite is the case. Among the gradual flares in Table 3 that occurred in the magnetically well-connected solar longitudes (west of E20), all but three produced detectable interplanetary protons, even though many of them did not produce nuclear γ rays above the GRS sensitivity threshold. For the three

exceptional flares the background proton fluxes from earlier proton events were high. Because there is ample evidence that the gradual flares in Table 3 have produced nuclear γ rays and/or interplanetary energetic protons, we may call them gradual GR/P flares.

The numbers of energetic (> 30 MeV) protons deduced both from γ-ray observations and from interplanetary particle observations are given in Table 4 (from Murphy and Ramaty 1985; Cliver et al. 1983). The ratio of the interplanetary proton number to the γ-ray-producing proton number varies greatly from flare to flare. But when the flares are divided into impulsive and gradual GR/P flares, we see that gradual flares show a higher average ratio.

b) Additional Differences in Coronal and Interplanetary Phenomena

Now that we have established that gradual GR/P flares produce larger numbers of interplanetary protons, let us investigate correlations with other upper coronal and interplanetary phenomena. Because we do not have such data at our disposal, we do not intend to perform a complete study. However, relevant data have recently been published in the literature. Cane and Stone (1984) studied interplanetary type II bursts observed with ISEE 3 from 1979 September to 1981 December. They report that interplanetary type II bursts (which indicate the existence of interplanetary shocks) are well correlated with soft X-ray LDEs and interplanetary particle events.

From Sheeley et al. (1984) and Kahler et al. (1984a, b, 1985) we find relevant information on observations of coronal mass ejections (CMEs). Sheeley et al. made a statistical comparison of metric type II bursts and CMEs, for the period 1979 May - 1982 October. They drew the following conclusions:

"First, type II bursts without CMEs were associated with short-lived (0.5 hr) soft X-ray events, but not with interplanetary shocks. Second, type II bursts with CMEs were associated with longer-lived soft X-ray events (3 hr on average) and interplanetary shocks, and the CMEs had speeds greater than 400 km/s. Third, CMEs without metric type II bursts were divided equally into groups faster and slower than 450 km/s. The faster CMEs were associated with interplanetary shocks, some of which originated on the visible disk where metric type II bursts should have been observed if they had occurred."

Evenson et al. (1984) studied interplanetary particle events observed in 1980, and concluded that the eletron-to-proton ratios are relatively large for GRL flares. However, their GRL flares with interplanetary particles happen to all be impulsive GRL flares (1980 June 7, June 21, and June 29). Two of the gradual flares observed in 1980 are found in Table 1 of Evenson et al. Interestingly, both of these flares (1980 March 27 and April 3) have small [e/p] ratios. For seven of the 49 events in Evenson et al., the peak flux of 25-45 MeV protons exceeds 100 protons $(m^2 \text{ s sr MeV})^{-1}$. The [e/p] ratios of these big proton events are "normal." For six of these seven events, the parent flares are identified. Inspecting the soft X-ray time profiles of these six flares, we found that five are LDEs, with one on 1980 February 6 being uncertain because of the soft X-ray data gap. Four events are common to Table 1 of Evenson et al. (1984) and Table 1 of Cane and Stone (1984), which lists interplanetary type II bursts. From these we find that proton events with interplanetary type II bursts have "normal" [e/p] ratios and are associated with X-ray LDEs. Because we interpret LDEs and interplanetary type II bursts as signatures of gradual GR/P flares, and because all the GR/P flares with relativley large [e/p] ratios are impulsive, we conclude that "electron richness" (or, equivalently, "proton poorness") is one of the characteristics of impulsive GR/P flares but not of gradual GR/P flares.

The event selection criteria used by Sheeley et al. (1984), Cane and

Stone (1984), Evenson et al. (1984), and Kahler et al. (1984a, b; 1985) are different from one another and different from ours. However, there are some common flares selected because the time periods covered in these studies are overlapping. In Table 5 we show the properties of GR/P flares obtained from the above studies. Blank entries in Table 5 mean that no information is available. We can clearly see from this table that phenomena occurring in the upper corona and interplanetary medium are well correlated with gradual GR/P flares but not with impulsive GR/P flares.

The duration of type II radio bursts is shown for both groups in Figure 9. The gradual GR/P flares on the average emit type II bursts for longer than the impulsive GR/P flares. The result for gradual GR/P flares is quite similar to that of proton flares shown by Kahler (1982). It is interesting to note that type II shocks that accelerate protons may be characteristically different from type II shocks that do not. It has been suggested that the former are bow shocks and the latter, blast wave shocks (Maxwell and Dryer 1982; Kahler et al. 1984a).

c) Discussion

The poor correlation between the number of γ-ray-producing protons and the number of interplanetary energetic protons could be due to the following two possibilities (cf. Cliver et al. 1983; Vlahos et al. 1985):

1. Both γ-ray-producing protons and interplanetary protons are accelerated by a common mechanism, but the escape probability varies greatly from flare to flare.

2. Interplanetary protons and γ-ray-producing protons are accelerated by different mechanisms.

Judging from the fact that gradual GR/P flares are associated with many

phenomena occurring in the upper corona and interplanetary medium, we propose that interplanetary energetic protons are mainly accelerated in the upper corona by shocks. This proposition is basically the same as the second-phase acceleration (cf. Wild, Smerd, and Weiss 1963; Svestka 1976; Ramaty et al. 1980).

However, for the following reasons we propose that even in gradual GR/P flares, acceleration of γ-ray-producing protons is a first-phase phenomenon. Even in gradual GRL flares, the time profile of nuclear γ rays is quite similar to the hard X-ray time profile of the same flare, although the former is delayed relative to the latter by tens of seconds (cf. Gardner et al. 1981; Chupp 1984). We have also seen in this paper that in gradual GR/P flares the high-energy (> 100 keV) X-ray time profiles are delayed relative to low-energy (50 keV) X-rays. Hinotori imaging observations show that in gradual GR/P flares the hard X-ray (16 ~ 40 keV) emission is mainly from extremely extended flare loops (Tsuneta et al. 1984; Takakura et al. 1984; Ohki et al. 1983). Because of the similarities of time profiles and relative delays, we believe that in gradual GR/P flares high-energy electrons and γ-ray-producing protons are accelerated in closed flare loops by the second-step mechanism (see Section II for definition). Furthermore, although the hard X-ray sources of gradual flares are high (1-5 x 10^9 cm), they are lower than the site of second-phase phenomena such as metric type II emissions (~ 10^{10} cm). In summary, in gradual GR/P flares both second-phase acceleration (for IP protons) and second-step acceleration (for γ-ray-producing protons, a first-phase phenomenon) take place, but in impulsive GR/P flares second-phase acceleration does not seem to be active.

The above thesis also explains the variation of [e/p] ratios found by Evenson et al. (1984). For gradual GR/P flares the second-phase

acceleration is the main source of interplanetary energetic electrons and protons. For impulsive GR/P flares, on the other hand, the escape of energetic particles accelerated by the second-step mechanism is probably the main source of interplanetary particles. Because of this difference in source, the [e/p] ratios of impulsive GR/P flares are expected to be different. As we have shown in Section IV, the electron-richness is not one of the characteristics of GR/P flares in general, but it is one of the characteristics of impulsive GR/P flares.

The hardening of the X-ray spectrum with time is interpreted as the result of second-step acceleration of relativistic electrons (Bai and Ramaty 1979; Bai et al. 1983b; Paper I). In all the gradual GR/P flares we have found spectral hardening, and we have concluded that second-step acceleration of protons must have taken place in all the gradual flares. Therefore, we again conclude that basically the same mechanism must accelerate γ-ray-producing protons and relativistic electrons (cf. Bai 1982; Paper I). The following hypothesis is compatible with the present finding that GR/P flares are different: During the first phase of GR/P flares a single mechanism accelerates electrons to relativistic energies and protons and heavy ions to γ-ray-producing energies but this mechanism is different from the primary mechanism which accelerates electrons to relatively low energies during non-GR/P flares. However, under this assumption, the mechanism operating during GR/P flares somehow has to produce spectral hardening, and the primary mechanism must be turned off during GR/P flares.

V. SUMMARY AND CONCLUSION

We have provided more evidence that γ-ray/proton (GR/P) flares are different from ordinary flares. Although impulsive and gradual GR/P flares are different from each other, qualititative differences are in second-phase phenomena. As far as first-phase phenomena are concerned, they are very similar except that time scales and spatial scales of gradual GR/P flares are considerably larger than those of impulsive GR/P flares. Nuclear γ-ray emission, flat hard X-ray spectra, and soft-hard-harder behavior of hard X-ray spectrum are found from both classes of flares. We have proposed that during the first phase of both impulsive and gradual GR/P flares an additional mechanism accelerates protons to > 1 MeV and electrons to relativistic energies in closed magnetic loops, using the particles accelerated by the primary (or first-step) mechanism as injection particles. This additional acceleration is called second-step acceleration (Bai and Ramaty 1979; Bai 1982; Bai et al. 1983b; Paper I). It seems that protons accelerated by the second-step mechanism have a low probability of escape into interplanetary space.

We have shown that GR/P flares can be divided into two classes--impulsive and gradual. In Table 6 we summarize the characteristics of the two classes of flare. Indeed, these two classes differ in many respects. Gradual GR/P flares have been recognized as a distinct class of flares from various kinds of observation. They have been called two-ribbon flares from H-α characteristics (Svestka 1976 and references therein), LDEs from soft X-ray characteristics (Saris and Shawhan 1973; Kahler 1977; Nonnast et al. 1982), extended flares from Skylab soft X-ray observations (Pallavicini, Serio, and Vaiana 1977), and proton flares from interplanetary particle observations (e.g., Svestka

1976; Kahler 1982). Recently, Tanaka (1983) and Tsuneta (1984) found from Hinotori observations that they are distinct in hard X-ray emission coming from extended coronal loops. Correlations among above-mentioned phenomena and CMEs (coronal mass ejections) and interplanetary phenomena have been studied by various authors (Kahler et al. 1978, 1984a; Sheeley et al. 1984; Cane and Stone 1984; Kahler 1982). The results of the present study are consistent with these earlier studies. The main contribution of this paper is study of hard X-ray and γ-ray emission and investigation of relationship between γ-ray-producing protons and interplanetary energetic protons. Although hard X-ray properties of two gradual flares of August 1972 have been studied (Hoyng, Brown, and van Beek 1976; Bai and Ramaty 1979), we have shown by doing the first systematic study that gradual GR/P flares exhibit distinct characteristics in hard X-ray emission. Note that we were able to select gradual GR/P flares by hard X-ray characteristics.

We have also proposed that, in addition to the second-step acceleration, protons and electrons are also accelerated in the open magnetic field configurations in the upper corona during gradual GR/P flares. This is the second-phase acceleration proposed by several researchers and widely accepted before the findings of SMM (e.g., Wild, Smerd, and Weiss 1963; de Jager 1969; Svestka 1976; Ramaty et al. 1980). The second-phase particles escape into the interplanetary medium and do not efficiently emit γ rays. After HEAO and SMM observations showed that nuclear γ rays are mainly emitted during the first phase, the reality of the second-phase acceleration was doubted by some researchers (Hudson et al. 1980; Riegler et al. 1982; Chupp 1982). However, the existence of second-phase acceleration in gradual GR/P flares with large fluxes of interplanetary protons is supported by the fact that they are accompanied by several upper coronal and interplanetary phenomena such as CMEs,

interplanetary type II bursts, type II metric bursts of long duration. Studying abundances of different species of particles, Mason, Gloeckler, and Hovstadt (1984) also recently argued that interplanetary energetic particles are accelerated by coronal shocks.

The relationship between flare classes and acceleration mechanisms is shown in Table 7. The classification of non-GR/P flares into thermal and non-thermal hard X-ray flares is based on Tanaka (1983). During gradual GR/P flares, full-fledged second-phase phenomena are observed, including proton acceleration. During most impulsive GR/P flares and some non-GR/P flares, metric type II and type IV radio bursts are observed, indicating the existence of coronal shocks. However, the coronal shocks originating from impulsive flares do not develop into interplanetary shocks (which produce kilometric type II bursts) and do not accelerate protons in large numbers.

Our concept of two classes of GR/P flares and two acceleration mechanisms for energetic protons and relativistic electrons can explain the finding (Cliver et al. 1983) that the correlation is poor between the number of γ-ray-producing protons and the number of interplanetary energetic protons. It can also provide a concise explanation for the discovery by Evenson et al. (1984) that GRL flares have relatively large [e/p] ratios. We have shown that, in fact, only impulsive GR/P flares are "electron rich" and that gradual GR/P flares have "normal" [e/p] ratios.

Part of the impetus for studying proton flares is that advance warning of proton events has a practical application. From the present study we find that gradual variations and the long duration of hard X-ray and microwave emission are good indicators of the production of interplanetary protons. Because worldwide radio observatories continuously observe the Sun, microwave observations are quite useful for forecasting proton events.

We find from the present study the following interesting point. We see in Table 1 that seven of the 11 impulsive GRL flares were observed in 1980 and four in 1981. However, from Table 3 we find that only three gradual flares were observed in 1980, but 15 in 1981. Therefore, it is not mere chance that HXIS operating in 1980 did not image many gradual flares while Hinotori operating in 1981 imaged many gradual flares. (Additionally, the imaging detector on Hinotori did not need pointing.)

This research was supported by NASA grants NGL 05-020-272 and NAGW-92, and ONR contract N00014-85-K-0111 (formerly N00014-75-C-0673) at Stanford University. The author thanks Drs. Alan Kiplinger and Brian Dennis for generously providing HXRBS spectral analysis, which is essential to this paper. He thanks Dr. S. Enome of Toyokawa Observatory, Dr. T. Kosugi of Nobeyama Solar Radio Observatory, and Dr. A. Magun of Berne Radio Observatory for sending the microwave time profiles for the flares studied in this paper. The author has benefitted from discussions with Professor Peter Sturrock and with Dr. David Forrest. He has also benefitted from participating in SMM Workshop meetings, which were funded by NASA. Comments by an anonymous referee helped sharpen some of the arguments in this paper.

TABLE 1
SMM GAMMA-RAY-LINE FLARES (1980-1981)

EVENT NUMBER	DATE	HARD X-RAY EMISSION PROPERTIES: PEAK TIME (UT)	SPIKE DURA. (s) (a)	TOTAL DURA. (s) (b)	H.X.R. DELAYS (s)	SPECTRAL INDEX AT PEAK	PEAK RATE (cts/s)	MICROWAVES: 9 GHz PEAK (sfu)	MRI	SOFT X-RAYS: GOES CLASS	DURATION (hr) (c)	RADIO BURSTS TYPE II/IV (d)	H-alpha: CLASS (e)	LOCATION (f)	HARD X-RAY SOURCE HEIGHT (10 cm) (g)
A. IMPULSIVE FLARES															
1	81 SEP 15	2114:40	7	290	-	3.8	28,000	400	0.14	X2	0.3	1 / 1,d	(2N)	N05 W82	---
2	80 JUN 7	0312:15	7	105	-	2.8	39,400	500	0.13	M7	0.1	2 / 1	1B	N12 W74	---
3	80 JUN 4	0654:37	10	90	-	4.0	35,200	600	0.17	M6	0.6	- / -	1B	S14 E59	---
4	80 JUN 29	1041:50	12	100	-	3.8	9,300	290	0.31	M4	0.5	3 / -	(1F)	S27 W90	---
5	80 JUL 1	1627:29	16	240	1.3	3.1	27,200	1,200	0.44	X2	0.2	3 / 2	1B	S12 W38	---
6	81 FEB 26	1425:55	17	120	0.8	3.2	22,500	780	0.35	X1	0.2	- / -	SB	S13 E53	---
7	80 JUN 21	0118:40	17	140	-	2.0	141,400	1,370	0.097	X2	0.3	2 / 3	(1B)	N19 W90	---
8	81 SEP 7	2223:20	18	230	1.5	3.0	8,500	940	1.1	--	gap	3 / -	SB	N11 E29	---
9	80 NOV 7	0204:55	28	480	-	4.5	86,600	7,800	0.90	X2	0.8	- / 1,d	2B	N09 W08	---
10	80 NOV 6	0348:00	72	>660	2.0	3.2	155,300	4,800	0.31	X9	1.0	3 / 3	2N	S13 E70	---
11	81 OCT 14	1706:30	75	(300)	3.5	3.1	44,200	2,700	0.61	X3	0.5	2 / 2,d	(SB)	S06 E86	0.7
B. GRADUAL FLARES															
12	81 APR 1	0146:04	96	1620	8	3.4	12,500	4,800	3.8	X2	4.0	3 / 2	3B	S43 W52	5.0
13	81 OCT 7	2301:35	110	(840)	10	3.1	33,700	9,500	2.8	X3	1.5	2 / -	(1N)	S17 E83	1.3
14	81 APR 10	1651:15	120	(900)	10	3.7	11,900	1,680	1.4	X2	1.0	3 / 2	2B	N07 W36	---
15	81 APR 27	0812:55	140	1950	11	3.4	56,200	11,000	2.0	X5	1.7	2 / 2	(1N)	N17 W90	1.7
16	81 MAY 13	0415:30	620	1920	37	3.6	5,400	4,600	8.5	X1	4.0	- / 1	3B	N10 E55	4.0
17	81 APR 26	1148:10	780	2700	120	3.4	7,800	10,000	12.8	X1	4.0	- / 3	2N	N15 W74	---

Notes to Table 1:

(a) Full width at 10 % of the maximum of the largest burst in the time profile of channels 5-7 (~135~218 keV).

(b) Full width at 10 % of the maximum of the whole flare in the time profile of channels 1-15 (~30~520 keV). For some GRL flares the entire duration of hard x-ray emission was not observed with SMM because of eclipses. For such flares the hard x-ray total duration was estimated using microwave time profiles, and such flares are indicated with parentheses in this column.

(c) Full width at 10 % of the maximum of the 1-8 A soft x-ray time profile measured with the GOES satellite.

(d) Numbers indicate intensity classifications (1: <50 sfu; 2: 50-500 sfu; 3: >500 sfu), and short bars indicate no report in Solar Geophysical Data (SGD), which in most cases means no occurrence.

(e) From standardized data in SGD. Parentheses indicate limb flares.

(f) From standardized datat in SGD.

(g) From Hinotori observations (Ohki et al. 1982; Takakura et al. 1982; Tsuneta et al. 1984).

TABLE 2.

ASSOCIATION WITH TYPE II AND IV BURSTS(1)

FLARE TYPE	NUMBER OF FLARES	NUMBER OF FLARES WITH TYPE II	NUMBER OF FLARES WITH WITH IV	NUMBER OF FLARES WITH WITH II AND IV
GRADUAL	2	2 (100%)	2 (100%)	2 (100%)
GRS	36	12 (33%)	14 (39%)	9 (25%)
NON-GRS	99	16 (16%)	12 (12%)	7 (7%)

NOTE: (1) For the period 1980 February 19 to 1981 February 19.

TABLE 3

GRADUAL FLARES OF 1980-1982

ORDER (HXRBS PEAK)	DATE	HARD X-RAY EMISSION PROPERTIES: PEAK TIME (UT)	SPIKE DURA. (min) (a)	TOTAL DURA. (min) (b)	H.X.R. DELAYS (sec)	SPECTRAL INDEX AT PEAK	PEAK FLUX (cts/s)	MICROWAVES: 9 GHz PEAK (sfu)	MRI	DELAYS (sec)	SOFT X-RAYS: GOES CLASS	DURATION (hr) (c)	RADIO BURSTS TYPE II/IV (d)	H-alpha: CLASS (e)	LOCATION (e)	NUCLEAR GAMMA RAYS (f)	TOTAL HXRBS COUNTS (10^6 cts)
1	81 APR 27	0812:55	2.3	33	11	3.4	56200	11000	2.0		X5	1.7	2 / 2	(1N)	N17 W90	Y	48.5
2	81 OCT 7	2301:35	1.9	(14)	10	3.1	33700	9500	2.8		X3	1.5	2 / -	(1N)	S17 E83	Y	>10.5
3	82 DEC 7	2352:41	9.0	44	40	2.8	23700	24700	10.3	50	X2	2.0	3 / 3	(1B)	S19 W86	Y	18.
4	82 NOV 26	0233:22	2.0	(20)	10	3.5	22700	8500	3.7	27	X4	3.3	3 / 3	(1N)	S12 W87	Y	>4.8
5	81 APR 1	0146:04	1.6	27	8	3.4	12500	4800	3.9	27	X2	4.0	3 / 2	3B	S43 W52	Y	7.2
6	81 APR 10	1651:15	2.0	(15)	10	3.7	11900	1680	1.4		X2	1.0	3 / 2	2B	N07 W36	Y	>3.6
7	81 APR 26	1148:10	13.0	45	120	3.4	7820	10000	12.8	330	X1	4.0	- / 3	2N	N14 W74	Y	3.6
8	81 MAY 13	0415:30	10.3	32	37	3.6	5420	4500	8.3	270	X1	4.0	- / 1	3B	N10 E55	Y	3.1
9	82 FEB 3	0114:45	3.0	21	20	3.3	4860	3000	6.2	20	X1	GAP	3 / 2	2B	S17 W29	Y	1.9
10	81 FEB 24	1226:35	5.0	20	20	3.5	3280	800	2.4		X1	0.8	2 / 1,d	1N	S11 E84	-	1.6
11	81 MAY 8	2233:25	3.1	23	35	3.2	3270	1300	4.0	40	M8	5.7	1 / 1	2B	N09 E37	-	1.7
12	82 DEC 8	1443:52	7.5	28	40	3.5	2450	1200	4.9	90	M6	5.0	- / 3	2B	N07 E68	-	1.6
13	81 OCT 18	1122:55	7.0	36	60	3.8	2020	1200	5.9	80	M2	6.0	- / 3	2B	S17 W52	-	0.98
14	80 APR 3	0719:05	5.0	(12)	60	3.8	1830	950	5.2	60	>M1	~4.0	3 / 1	2N	N30 W16	-	--
15	82 JAN 31	1330:35	1.5	12	5	3.5	1820	1200	6.6	10	M2	1.0	3 / -	1B	S12 E20	-	0.33
16	81 APR 14	2340:00	2.6	24	17	3.2	1790	2300	12.8	20	M3	4.5	1 / 1	1N	N13 E73	-	0.77
17	81 JUL 20	1318:30	1.5	22	12	4.0	1540	560	3.6		M5	2.5	3 / -	1B	S25 W75	-	0.75
18	81 JAN 25	0905:31	6.2	36	40	3.4	1280	3500	27.3	60	M9	2.0	3 / 1,d	(SN)	S12 E90	-	1.2
19	81 NOV 14	2202:10	5.0	17	60	4.1	1010	850	8.4	270	M5	2.0	2 / 2	2B	N15 W49	-	0.40
20	81 DEC 9	1924:10	3.5	36	15	3.5	820	320	3.9	40	M4	2.5	- / -	?B	N21 W15	-	0.49
21	80 NOV 14	1830:25	2.5	24	?	4.5	720	350	4.9		M2	>1.5	- / -	1B	S13 W50	-	0.14
22	80 MAR 27	1259:00	2.5	18	30	3.7	700	560	8.0	40	M1	6.0	- / 3	2B	N29 E70	-	0.37
23	81 JUN 22	1454:20	4.2	25	-	3.3	330	560	16.7	40	M1	3.0	- / -	SB	N17 E39	-	0.10

Notes to Table 3:

(a) Full width at 10 % of the maximum of the largest burst in the time profile of channels 5-7 (~135~218 keV).

(b) Full width at 10 % of the maximum of the whole flare in the time profile of channels 1-15 (~30~520 keV). For some GRL flares the entire duration of hard x-ray emission was not observed with SMM because of eclipses. For such flares the hard x-ray total duration was estimated using microwave time profiles, and such flares are indicated with parentheses in this column.

(c) Full width at 10 % of the maximum of the 1-8 A soft x-ray time profile measured with the GOES satellite.

(d) Numbers indicate intensity classifications (1: <50 sfu; 2: 50-500 sfu; 3: >500 sfu), and short bars indicate no report in Solar Geophysical Data (SGD), which in most cases means no occurrence.

(e) From standardized data in SGD. Parentheses indicate limb flares.

(e) H-alpha data are from SGD Comprehensive Report. Parentheses indicate limb flares.

(f) Standardized data from SGD Comprehensive Report.

(g) From Rieger (1982) and Share et al. (1983).

TABLE 4
NUMBER OF ENERGETIC (>30MeV) PROTONS (a)

	Date of Flare	Location	Gamma-Ray Producing Protons	Inter-planetary Protons	I.P. ----- GRP	Impulsive or Gradual?
1.	1972 Aug 4	N14 E08	1.0 E33	4.3 E34	43	Gradual
2.	1978 Jul 11	N18 E43	1.6 E33	(b)	?	Gradual
3.	1979 Nov 9	S12 W02	3.6 E32	none	<<1	Impulsive
4.	1980 Jun 7	N12 W74	9.3 E31	8.0 E29	8.6E-3	Impulsive
5.	1980 Jul 1	S12 W38	2.8 E31	<4.0 E28	<1.4E-3	Impulsive
6.	1980 Nov 6	S13 E70	1.3 E32	3.0 E29	2.3E-3	Impulsive
7.	1981 Apr 10	N07 W36	1.4 E32	7.0 E31	0.5	Gradual
8.	1982 Jun 3	S09 E72	2.9 E33	3.6 E32	1.2E-1	(c)
9.	1980 Jun 21	N19 W90	7.2 E32	1.5 E31	2.1E-2	(d)
10.	1981 Dec 9	N12 W16	<2.0 E31	1.0 E32	>5.0	Gradual

Notes:

(a) Proton number estimates are from Cliver et al. (1983) and Murphy and Ramaty (1985). The IP proton number for the 1981 April 10 flare was estimated by us.

(b) This flare produced interplanetary protons, but it is difficult to estimate their number because of another big proton event observed on the next day.

(c) This flare shows impulsive behavior in the beginning but becomes gradual later. McDonald and van Hollebeke (1985) and Murphy and Ramaty (1985) claim that there is evidence of second-phase acceleration for this flare.

(d) This flare is impulsive, but McDonald and van Hollebeke (1985) show that there is a small increase of IP proton flux ~3 hours before the onset of this flare and these particles could have been accelerated further during this flare.

TABLE 5
ADDITIONAL PROPERTIES OF GR/P FLARES

A. IMPULSIVE GR/P FLARES

NUMBER IN TABLE 1	DATE	INTER-PLANETARY TYPE II(a)	CORONAL MASS EJECTION(b)	ELECTRON TO PROTON RATIO(c)
1	81 SEP 15		NO	
2	80 DEC 18			
3	80 JUN 7		NO	LARGE (<493.3)
4	80 JUN 4			
5	80 JUN 29			LARGE (3530.0)
6	80 JUL 1			
7	80 NOV 12			
8	81 FEB 26			
9	80 JUN 21			LARGE (548.3)
10	81 SEP 7			
11	80 NOV 7			
12	80 NOV 6		YES	
13	81 OCT 14			

B. GRADUAL GR/P FLARES

NUMBER IN TABLE 3	DATE	INTER-PLANETARY TYPE II(a)	CORONAL MASS EJECTION(b)	ELECTRON TO PROTON RATIO(c)
1	81 APR 27			
2	81 OCT 7	YES	YES	
3	82 DEC 7			
4	82 NOV 26	YES		
5	81 APR 1	YES	YES	
6	81 APR 10		YES	
7	81 APR 26	YES		
8	81 MAY 13	YES		
9	82 FEB 3			
10	81 FEB 24			
11	81 MAY 8	YES	YES	
12	82 DEC 8			
13	81 OCT 18			
14	80 APR 3		YES	NORMAL (<14.46)
15	82 JAN 31			
16	81 APR 14			
17	81 JUL 20			
18	81 JAN 25			
19	81 NOV 14		YES	
20	81 DEC 9	YES	YES	
21	80 NOV 14			
22	80 MAR 27			NORMAL (<13.62)
23	81 JUN 22		YES	

(a) From Cane and Stone (1984) and Cane (1984).

(b) From Sheeley et al. (1984) and Kahler et al. (1984a, 1984b, 1985).

(c) From Evenson et al. (1984). The numbers in parentheses indicate the electron to proton flux ratio in 25-45 MeV multiplied by 10000.

TABLE 6
IMPULSIVE AND GRADUAL GAMMA-RAY/PROTON FLARES

	CATEGORIES	IMPULSIVE FLARES	GRADUAL FLARES	COMMENTS
1	H.X.R. SPECTRUM	HARD (average index 3.5)	HARD (average index 3.5)	
2	H.X.R. SPECTRAL HARDENING	SOME (6 out of 13)	YES (22 out of 23)	SAME
3	ASSOCIATION WITH TYPE II OR IV	GOOD (9 out of 13)	GOOD (20 out of 23)	
4	HIGH-ENERGY H.X.R. DELAY	SHORT (< 4 s)	LONG (> 8 s)	
5	H.X.R. SPIKE DURATION	< 90 s (<30 s)	> 90 s	
6	H.X.R. TOTAL DURATION	< 10 min	> 10 min	
7	SOFT X-RAY DURATION	< 1 hr	> 1 hr	
8	H-alpha AREA	SMALL	LARGE	
9	LOOP HEIGHT	LOW (<10^9 cm)	HIGH (>10^9 cm)	DIFFERENT (1)
10	MRI	< 1.0	> 1.0	
11	AVG. TYPE II DUR.	14 min	25 min	
12	$\left[\frac{\text{I.P. PROTONS}}{\text{ON SITE PROTONS}}\right]$	SMALL (<<1)	LARGE (>1)	
13	INTERPLANETARY SHOCK	NO	YES	
14	CORONAL MASS EJECTION	SOME	YES	
15	[e/p] RATIO	LARGE	NORMAL	

Notes: (1) Characteristics # 9, 12, 13, 14, and 15 are extrapolated from observations available for relatively small numbers of flares.

Table 7. FLARE CLASSIFICATION AND RELATED ACCELERATION

Flare Class	Flare Phase	Acceleration	Species of Particles	Observational Signatures
A. GR/P Flares				
1. Gradual	First Phase	Primary Acceleration	Electrons (<200 keV)	Hard X-rays
		Second-Step Acceleration	Electrons (>200 keV) Protons & ions (>1 MeV)	Hard X-rays* Nuclear gamma rays
	Second Phase	Second-Phase Acceleration	Protons & ions (>1 MeV) Electrons	IP Protons Metric Type II IP Type II
2. Impulsive	First Phase	Primary Acceleration	Electrons (<200 keV)	Hard X-rays
		Second-Step Acceleration	Electrons (>200 keV) Protons & ions (>1 MeV)	Hard X-rays* Nuclear gamma rays IP Protons (low flux)
	Second Phase	Second-Phase Acceleration	Electrons No Appreciable Protons	Metric Type II
B. Non-GR/P Flares				
1. Nonthermal Hard X-ray	First Phase	Primary Acceleration	Electrons (<200 keV)	Hard X-rays
	Second Phase	Second-Phase Acceleration	Electrons	Metric Type II (only for some)
2. Thermal Hard X-ray	First Phase	Plasma Heating	Hot ($\sim 40 \times 10^6$ K) Plasma	Thermal Hard X-rays

*spectral hardening and flat spectrum

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FIGURE CAPTIONS

Fig. 1. Distribution of hard X-ray spectral indices measured at HXRBS peaks. Panel (a) shows the result for non-GRS flares, and panel (b) shows the results for GRS flares with GRL flares indicated by shaded area.

Fig. 2. Flare size distributions as functions of HXRBS total count, > 270 keV fluence, and 4-8 MeV excess fluence. Note that number of flares increases much more rapidly with the decrease of HXRBS total count than with the decrease of > 270 keV fluence or 4-8 MeV excess fluence.

Fig. 3. Correlation diagram between peak count rates measured by HXRBS and peak flux densities of ~ 9 GHz microwaves for 1980 through 1981. The median value of MRIs is about 1. The three straight diagonal lines indicate constant values of MRI, 1/4, 1, and 4. The large dots indicate GRL flares. Gradual flares are shown by crosses (x). Note that all the gradual flares with HXRBS peak rates > 5000 counts/s are GRL flares.

Fig. 4. Evolution of hard X-ray flux and spectrum for the 1982 December 7-8 flare. The top panel shows the time profile of the HXRBS total count rate in ~ 30 - ~ 500 keV. The middle and the bottom panels show the evolution of A, 50 keV flux, and b, the spectral index, where A and b are obtained by fitting the data with the following single power-law spectrum:

$$J(E) = A\,(E/50\ \mathrm{keV})^{-b} \quad .$$

In this figure we see the long duration and gradualness of the hard X-ray emission and the spectral hardening during each spike-burst of the flare. The duration of type II radio burst is shown in the top panel. Note that in the beginning the hard X-ray time profile shows rapid variations (impulsive behavior). (Figs. 4-7, courtesy of Alan Kiplinger)

Fig. 5. Evolution of hard X-ray flux and spectrum for the 1981 May 8 flare. Spectral hardening is observed in every spike burst. In this flare the hard X-ray time profile shows gradual behavior from the beginning.

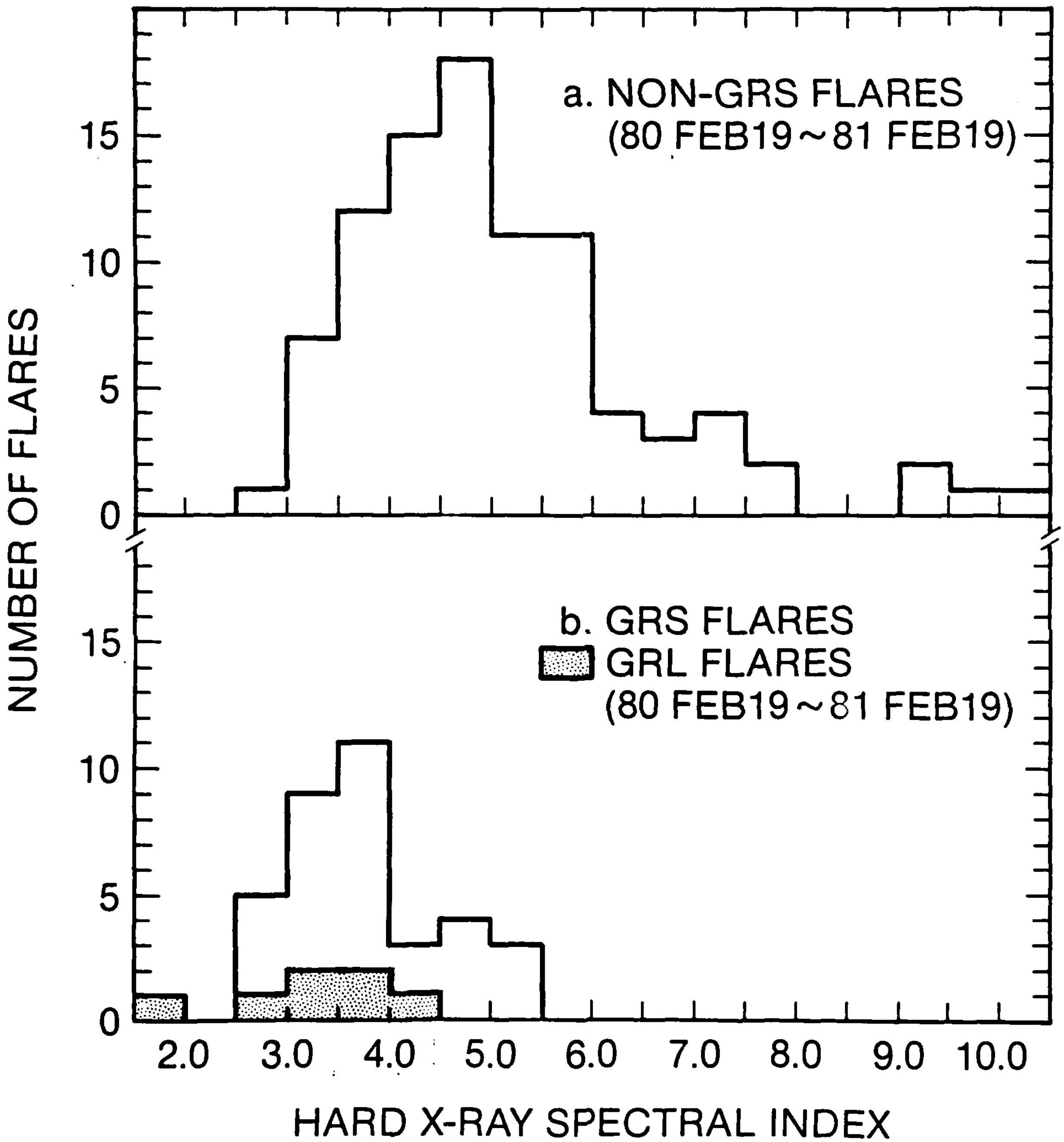
Fig. 6. Evolution of X-ray flux and spectrum for the 1980 April 3 flare. SMM emerged from the Earth's shadow at ~ 0717:30 UT. According to the Toyokawa observation, 9.4 GHz microwave emission showed impulsive behavior during the period 0707-0713 UT. A type II metric burst started at 0706 UT, and the 9.4 GHz flux density also started to increase at 0706 UT.

Fig. 7. Evolution of hard X-ray flux and spectrum for the 1982 January 31 flare. Impulsive behavior is observed in the beginning (1321-1324 UT). Note from Figs. 3 - 6 that in gradual flares type II and type IV radio bursts are observed while hard X-ray emission is still at full strength. In impulsive flares type II and type IV bursts are observed after hard X-ray emission decays.

Fig. 8. Hard X-ray spectral index versus peak count rate. Solid dots (•) represent all HXRBS flares observed during the interval from 1980 February 19 to 1981 February 19 to have peak count rates > 1000 counts/s, excluding the flares for which the real X-ray maxima were not observed with HXRBS due to spacecraft eclipses or other causes. Circles (O) represent the GRL flares in Table 1; crosses (X), gradual GR/P flares in Table 3. All spectral indices are measured at the peaks of hard X-ray emission. Overlapping of different symbols in this figure is not due to chance; overlapping of a circle and a solid dot indicates a GRL flare observed before 1981 Febraury 19, and overlapping of a circle and a cross indicates a gradual flare

with nuclear γ-ray observation. It is evident that GR/P flares that include flares indicated by circles and crosses have flatter X-ray spectra on the average than ordinary flares. We notice that flares with larger peak count rates have flatter spectra, on the average. It is plausible that different classes of flares have different distributions in peak HXRBS count rates. For example, the highest peak HXRBS count rate observed among impulsive GR/P flares is > 10^5 cts/s, whereas among gradual GR/P flares it is 5.6 x 10^4 cts/s (1981 April 27 flare). The data in this figure are consistent with the assumption that thermal hard X-ray flares (cf. Table 6), which emit thermal bremsstrahlung with steep spectra in the HXRBS energy range, have HXRBS peak rates less than 10,000 counts/s. None of the flares with spectral indices > 6 produced type II or type IV bursts. (Data from Brian Dennis)

Fig. 9. Distribution of durations of type II radio bursts. The panel (a) and (b) are from Kahler (1982). II events are flares with type II metric bursts observed in magnetically well-connected longitudes but without observable interplanetary energetic protons, and P events are flares with both type II and interplanetary protons. The results for gradual GR/P flares are very similar to those of P events, as one would expect. Type II durations of impulsive GR/P flares are on the average shorter than those of gradual GR/P flares, but somehwat longer than those of II events.



a. NON-GRS FLARES
(80 FEB19 ~ 81 FEB19)
b. GRS FLARES
GRL FLARES
(80 FEB19 ~ 81 FEB19)
NUMBER OF FLARES
0
5
10
15
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
HARD X-RAY SPECTRAL INDEX

Fig. 1

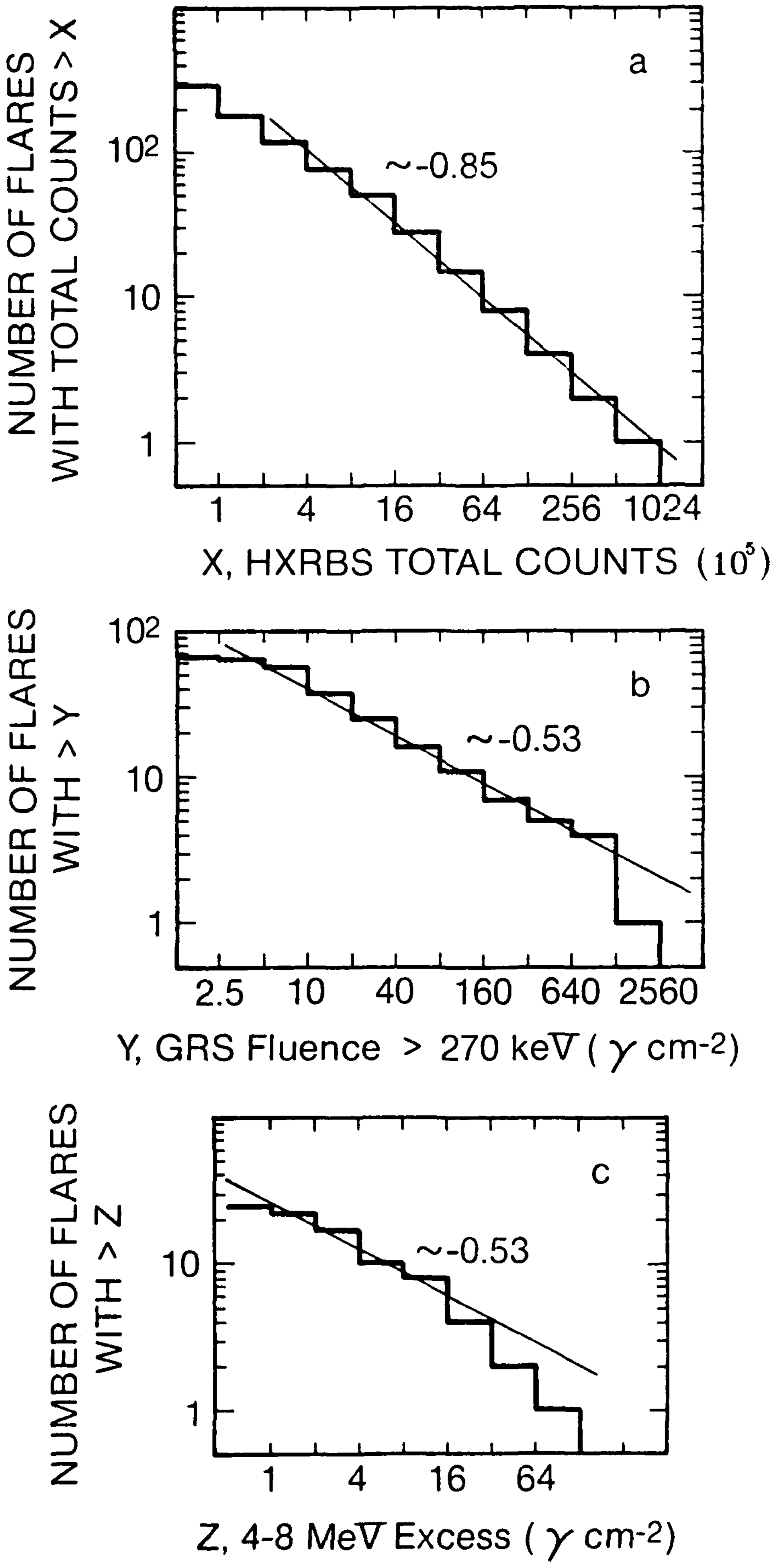
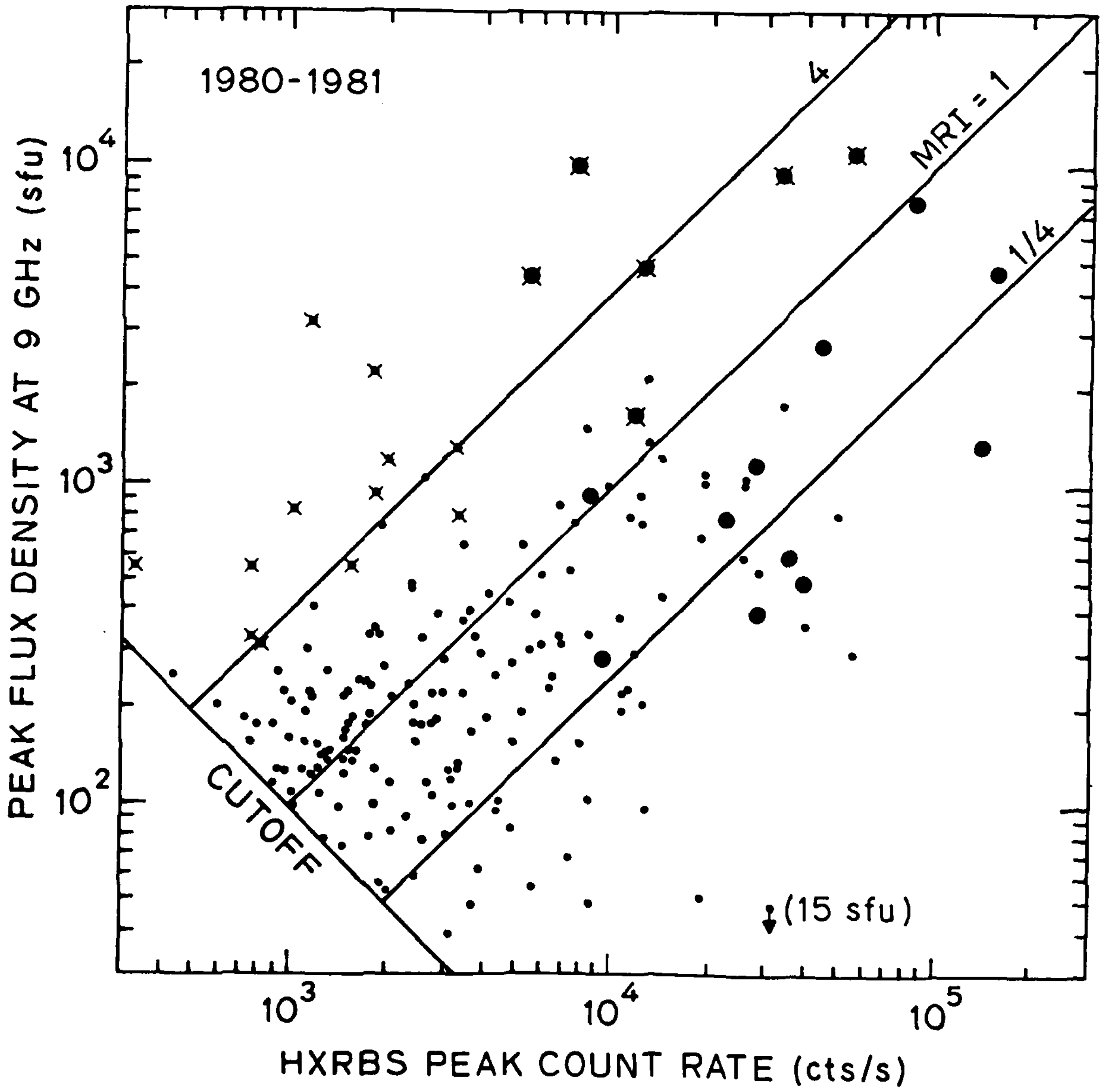
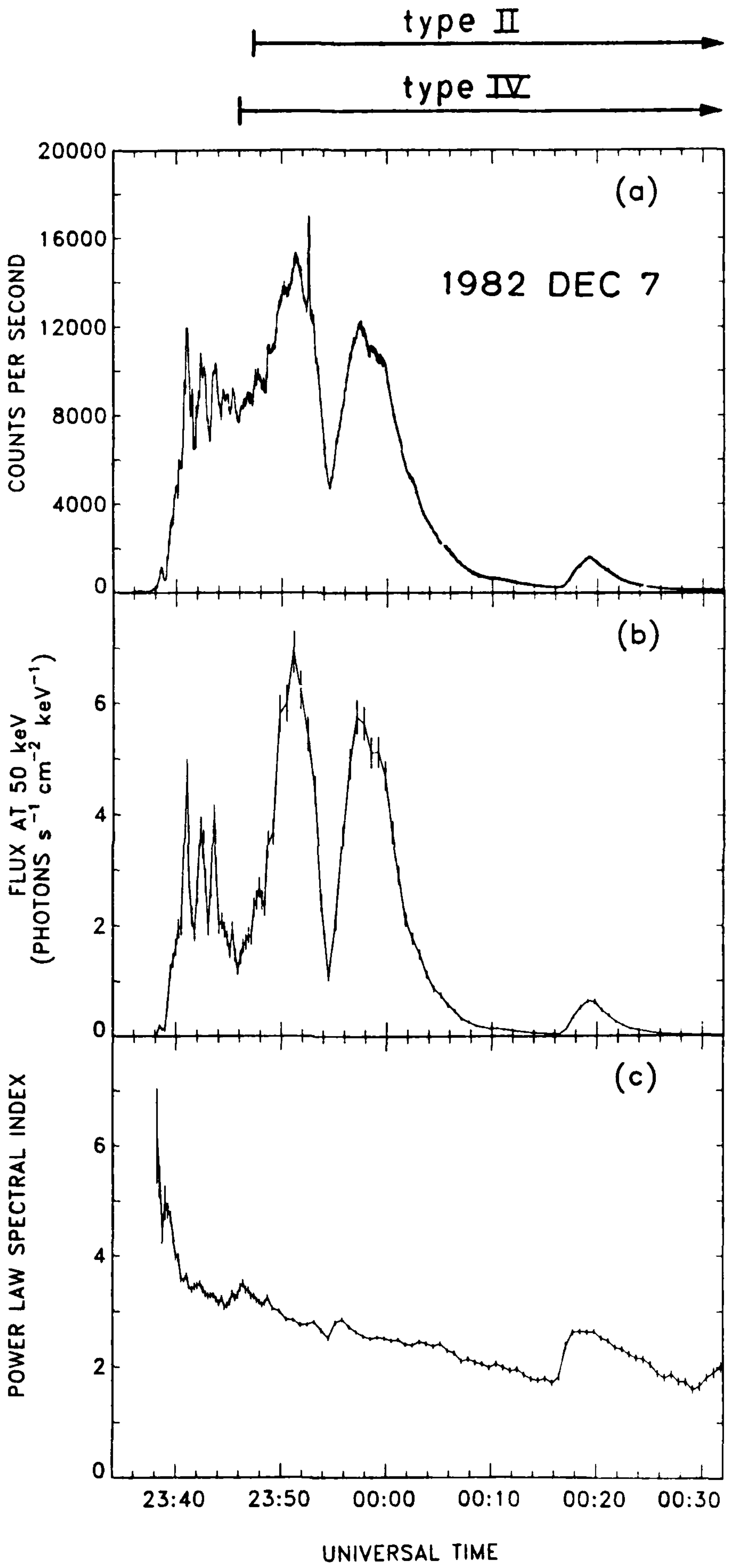

NUMBER OF FLARES WITH TOTAL COUNTS > X
a
~-0.85
10²
10
1
1
4
16
64
256
1024
X, HXRBS TOTAL COUNTS (10⁵)
NUMBER OF FLARES WITH > Y
b
~-0.53
10²
10
1
2.5
10
40
160
640
2560
Y, GRS Fluence > 270 keV (γ cm-2)
NUMBER OF FLARES WITH > Z
c
~-0.53
10
1
1
4
16
64
Z, 4-8 MeV Excess (γ cm-2)

Fig. 2



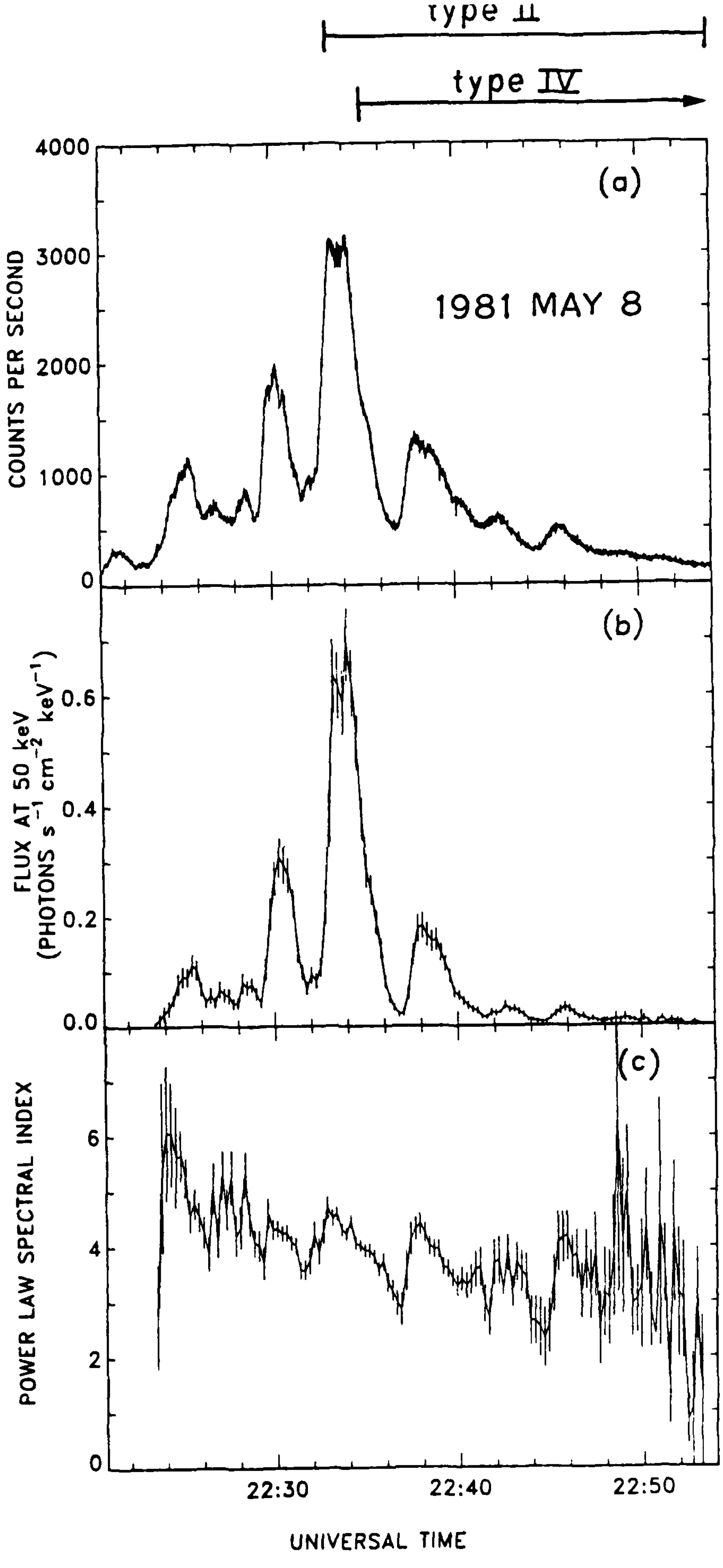
1980-1981
4
MRI = 1
1/4
CUTOFF
(15 sfu)
PEAK FLUX DENSITY AT 9 GHz (sfu)
HXRBS PEAK COUNT RATE (cts/s)
10^2
10^3
10^4
10^5

Fig. 3



type II
type IV
(a)
1982 DEC 7
COUNTS PER SECOND
20000
16000
12000
8000
4000
0
(b)
FLUX AT 50 keV
(PHOTONS s^{-1} cm^{-2} keV^{-1})
6
4
2
0
(c)
POWER LAW SPECTRAL INDEX
6
4
2
0
23:40
23:50
00:00
00:10
00:20
00:30
UNIVERSAL TIME

Fig. 4



type II
type IV
4000
3000
2000
1000
0
COUNTS PER SECOND
(a)
1981 MAY 8
(b)
FLUX AT 50 keV
(PHOTONS s^{-1} cm^{-2} keV^{-1})
0.6
0.4
0.2
0.0
(c)
POWER LAW SPECTRAL INDEX
6
4
2
0
22:30
22:40
22:50
UNIVERSAL TIME

Fig. 5

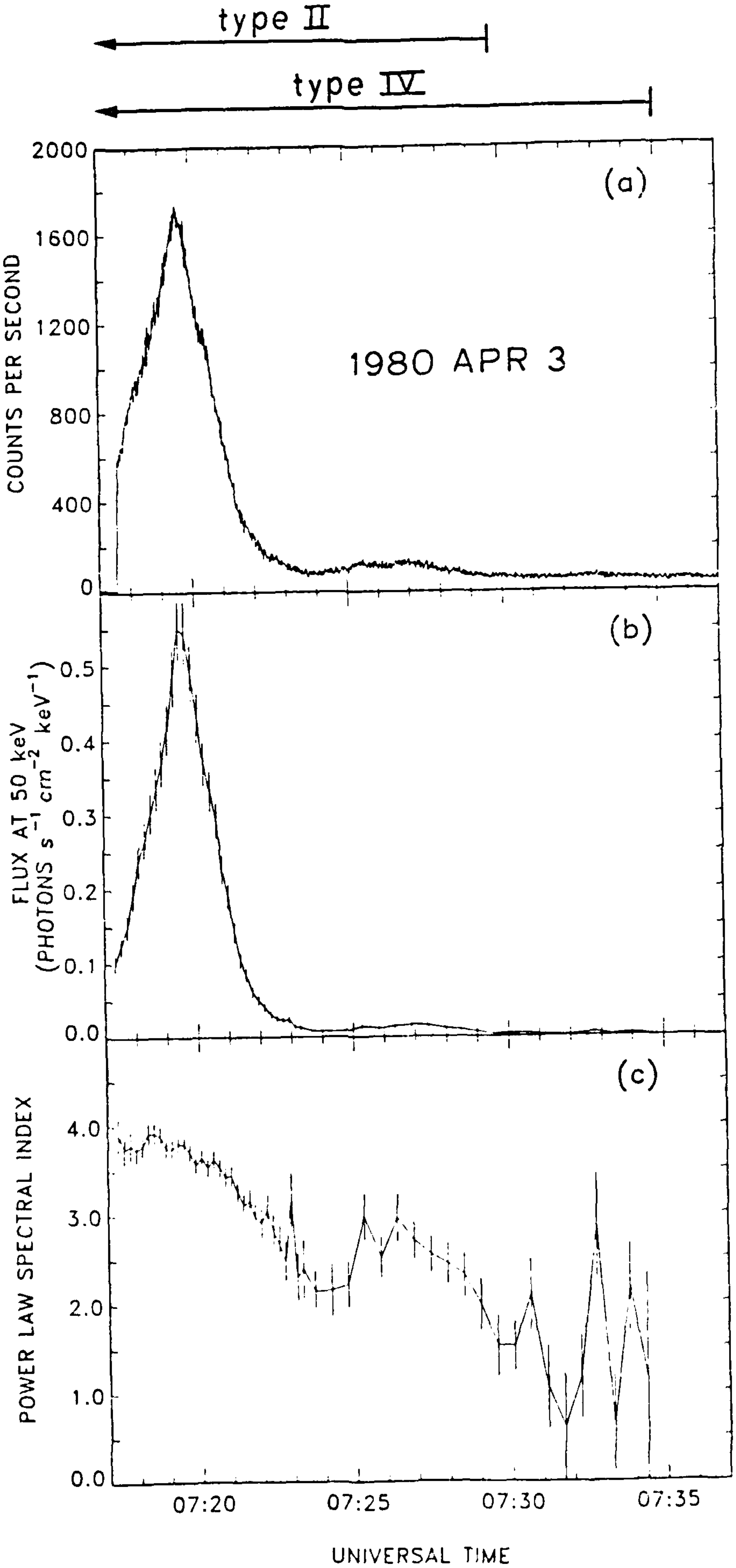
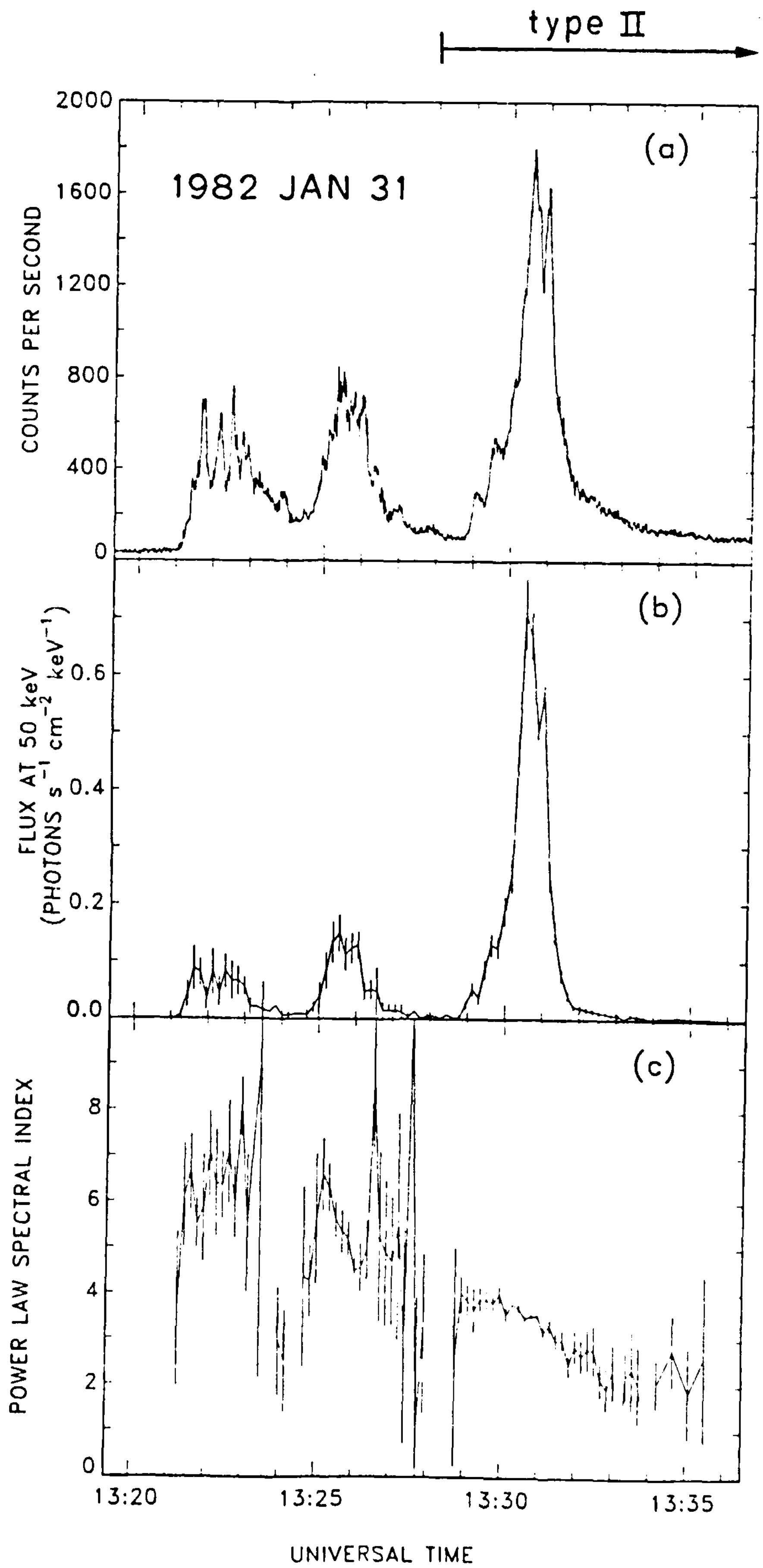

type II
type IV
2000
1600
1200
800
400
0
COUNTS PER SECOND
(a)
1980 APR 3
FLUX AT 50 keV
(PHOTONS s^{-1} cm^{-2} keV^{-1})
0.5
0.4
0.3
0.2
0.1
0.0
(b)
POWER LAW SPECTRAL INDEX
4.0
3.0
2.0
1.0
0.0
(c)
07:20
07:25
07:30
07:35
UNIVERSAL TIME

Fig. 6



type II
(a)
1982 JAN 31
COUNTS PER SECOND
2000
1600
1200
800
400
0
(b)
FLUX AT 50 keV
(PHOTONS s^{-1} cm^{-2} keV^{-1})
0.6
0.4
0.2
0.0
(c)
POWER LAW SPECTRAL INDEX
8
6
4
2
0
13:20
13:25
13:30
13:35
UNIVERSAL TIME

Fig. 7

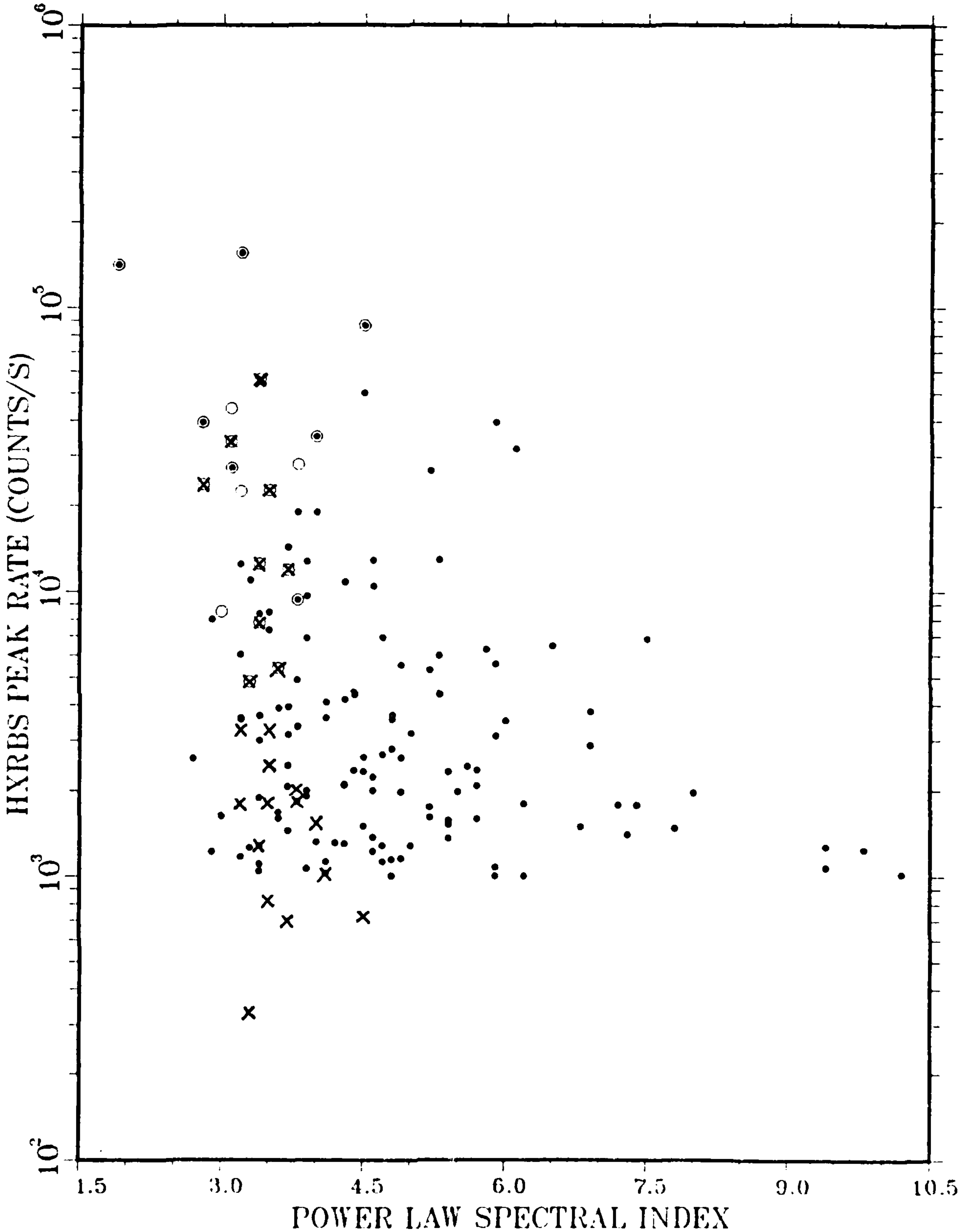

HXRBS PEAK RATE (COUNTS/S)
10^2
10^3
10^4
10^5
10^6
1.5
3.0
4.5
6.0
7.5
9.0
10.5
POWER LAW SPECTRAL INDEX

Fig. 8

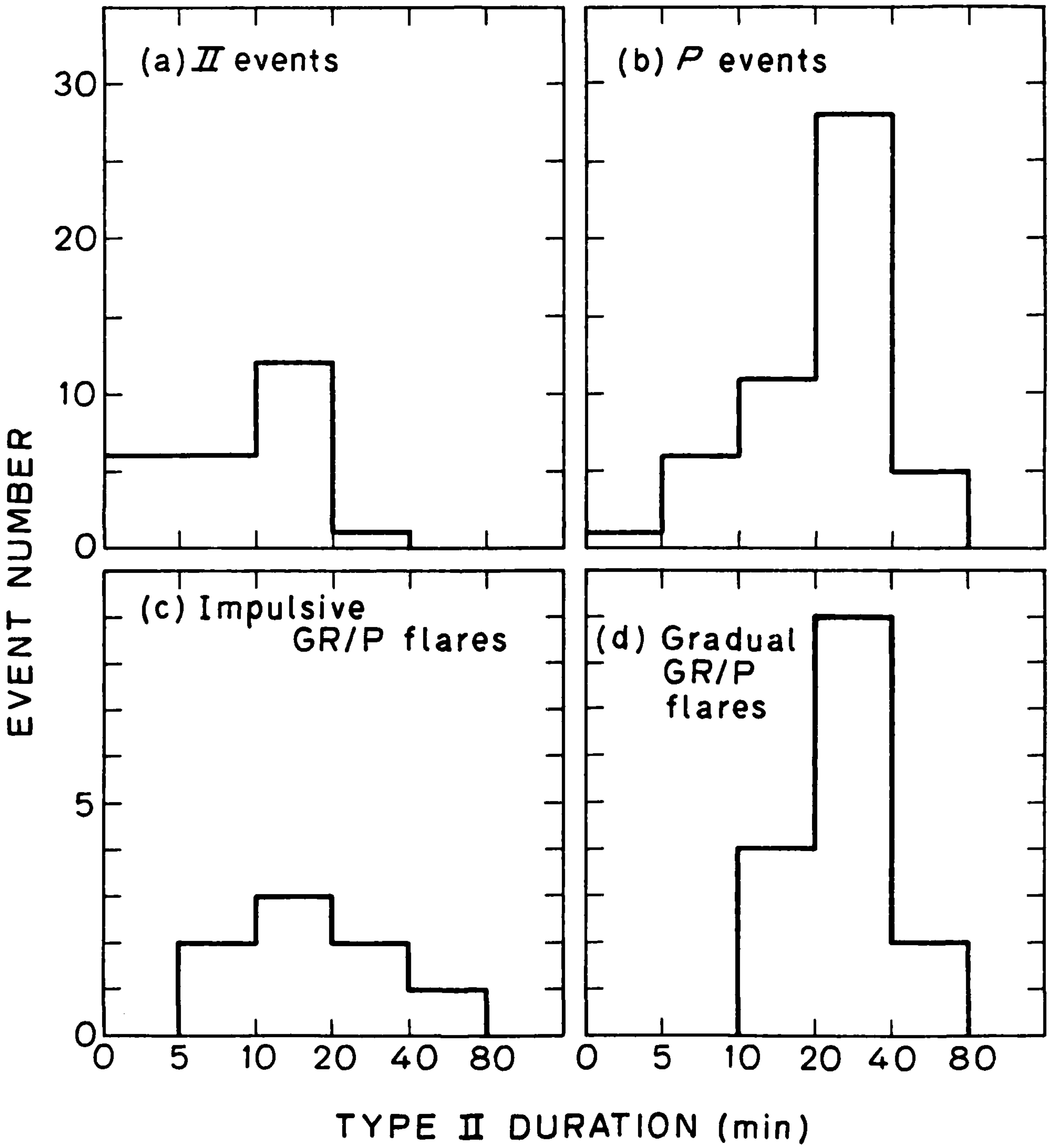

(a) II events
(b) P events
(c) Impulsive GR/P flares
(d) Gradual GR/P flares
EVENT NUMBER
30
20
10
0
5
0
0
5
10
20
40
80
0
5
10
20
40
80
TYPE II DURATION (min)

Fig. 9

END

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